MEASUREMENT OF THE PROFILES OF 'SUPER-SMOOTH' SURFACES USING OPTICAL INTERFEROMETRY

M. J. Downs
National Physical Laboratory, Teddington, Middlesex, England.

N. M. Mason and J. C. C. Nelson
Department of Electrical and Electronic Engineering, University of Leeds, England

ABSTRACT

Interferometers are widely used for measuring the profiles of 'super-smooth' surfaces. The most sensitive of these instruments employ a 'common-path' design with the two interfering beams being reflected from different areas of the test surface, making the interferometer insensitive to vertical motion of the surface. When these systems are applied to the measurement of surface 'roughness' the shortest surface wavelength that can be measured depends upon both the wavelength of the measurement radiation and the numerical aperture of the probe beam optics. The longest surface wavelength depends upon the optical configuration of the interferometer.

A profiling interferometer will be briefly described that has a sensitivity to surface height of better than 0.01 nm and a surface wavelength range from 0.5 to 15 micrometres.

The results of measurements on a number of surfaces using this instrument will be shown and the methods used for analysing these will be discussed.

1. INTRODUCTION

To meet a growing need for the non-destructive measurement of the profiles of 'super-smooth' surfaces in a wide variety of applications, a number of optical systems have been developed over recent years. The most sensitive of these instruments are 'common-path' interferometers with the interfering beams reflected from different areas of the surface[1,2,3,4]. Using interferometric techniques the required sensitivity to variations in surface height can be readily obtained by measuring the path difference between the two interfering beams, which varies according to the surface profile when the beams move across the surface.

The shortest surface wavelength that can be measured by these systems is controlled both by their diffraction limit and any aberrations that are present in the optics. The longest wavelength depends upon the optical configuration of the interferometer.

The NPL surface profilometer[4] (Figure 1) uses a microscope objective with a numerical aperture of 0.5 in conjunction with a birefringent lens to provide a focused spot from a Helium Neon laser (λ 633 nm), with the first minimum in the diffraction pattern 1.54 µm in diameter and a defocussed orthogonally polarised beam 10 µm in diameter. Fourier analysis of traces obtained from a number of surfaces indicates that with this objective the NPL system has a surface wavelength range from 0.5 to 15 µm.

The instrument has been used to measure shorter surface wavelengths both by using a microscope objective with a numerical aperture of 0.9 and by operating the system in a confocal microscope mode[5] with a 160 mm lens and a 20 µm diameter aperture in front of the photodetector. However it will be appreciated that in practice these modifications were concomitant with finer focus and alignment requirements for the system. The instrument measures the surface under examination by repeatedly scanning 100 µm across the specimen using a piezo-electrically driven strip-hinge motion, and results obtained from silica surfaces fabricated for use in the X-ray field and Zerodur ring laser gyroscope mirror surfaces are described.

2. MEASUREMENT OF THE PROFILES OF 'SUPER-SMOOTH' SILICA SURFACES

A typical trace obtained by the NPL surface profilometer from a silica surface prepared at the laboratory for use in the field of X-rays is shown in Figure 2. The low signal-to-noise ratio obtained from the instrument can be seen by comparing the section of the trace where the specimen is being scanned with that where the specimen is stationary. The differences between the forward and reverse scan traces result from hysteresis in the piezo-electric element driving the strip-hinge specimen scanning stage which also introduces slight differences in the scanned area and the focal position. The full scale deflection of the trace in Figure 2 is 0.2 nm and the peak-to-peak noise level of the system is less than 0.01 nm. However, although the instrument is capable of measuring

variations in the surface height to this sensitivity it will be appreciated that this does not imply that the instrument has an absolute vertical resolution of this scale as the trace displayed is an interferometrically obtained path difference between the averaged surface levels of a focused probe beam and defocussed reference beam. The information provided by the trace is dependent upon both the surface frequency range realised by these beams and the characteristics of the surface irregularities that give rise to the signal. Comparisons of measurements of the profile over a similar length of the surface with a modified mechanical stylus measuring system (Talystep) at the laboratory, realised agreements between R_a values (the arithmetic mean of the departures of the roughness profile from the mean line) for the surface of the order of ± 10%, confirming that optical interferometery provides a valuable non-destructive qualitative assessment of the surface finish of 'super-smooth' surfaces.

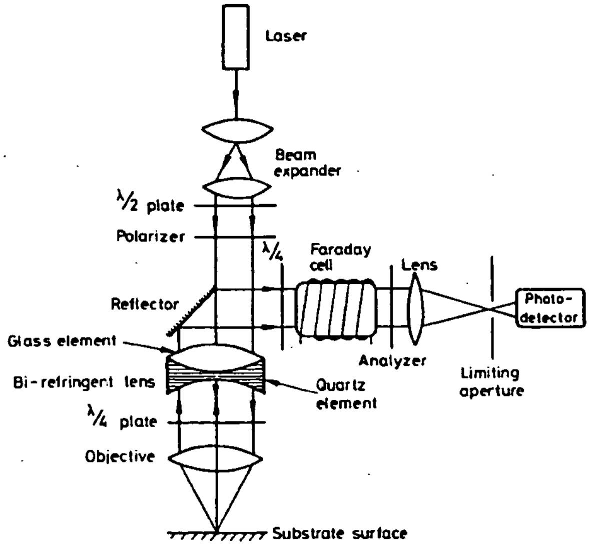

Fig 1 NPL polarization interferometer

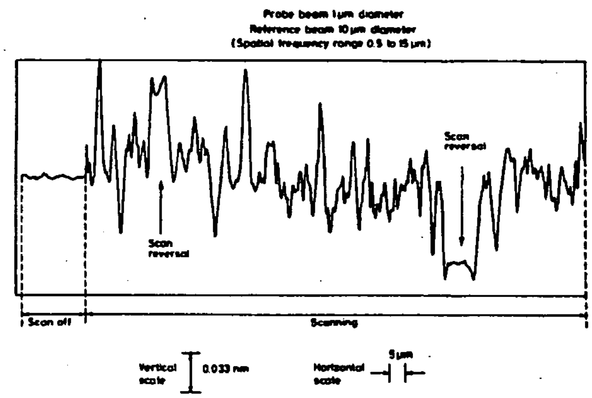

Fig 2 Surface profile of polished silica

3. SYSTEM RESPONSE CHARACTERISTICS

As mentioned in the previous section, the signal from interference profilometers is a measurement of the optical path differences between a probe beam and a reference beam. Because this is performed interferometrically it is the amplitudes of the interfering beams which are of importance. For the large defocussed reference beam variations in amplitude reflected from the illuminated surface will be negligible in comparison with those of the focused probe beam[6].

The amplitude distribution of the probe will be that of Figure 3, the well-known Airy disc distribution due to diffraction by a circular aperture. The amplitude at a point P in the image plane is described by

$$u(P) = \left(\frac{2J_1(Krw)}{(Krw)}\right) U_o$$

where u(P) = Amplitude function at point P

$J_1(x)$ = Bessel function of first kind, order 1 = $\frac{1}{2\pi i}\int_0^{2\pi} e^{i(v+x\cos v)}dv$

x = Krw

K = wave number = $\frac{2\pi}{\lambda}$

λ = illuminating wavelength

r = radius of circular aperture

w = radial distance of point P from centre of image plane.

U_o = Intensity at centre of image plane.

As can be seen from Figure 3 this involves distinct concentric rings in the amplitude, with differences in radii smaller than the radius of the central disc of the distribution. In practice on surfaces with certain roughness characteristics, this can lead to the system being responsive to surface wavelengths smaller than the effective diameter of the probe beam. Figure 4 shows a comparison of the Fourier transforms of the responses to a Zerodur ring laser gyro mirror surface in conventional and confocal modes of operation.

For a samples signal h(t) the DFT (Discrete Fourier Transform) H(f) is defined as

$$H\left(\frac{n}{NT}\right) = T\sum_{K=0}^{N-1} h(KT)e^{-2\pi i\frac{nK}{N}}$$

where

N = Total number of samples used from time domain

T = width of each sample in time domain

K = sample number in time domain

n = sample number in frequency domain = 0,1, ..., N/2

The factor of T is used to give agreement between the Fourier Transform and the DFT.

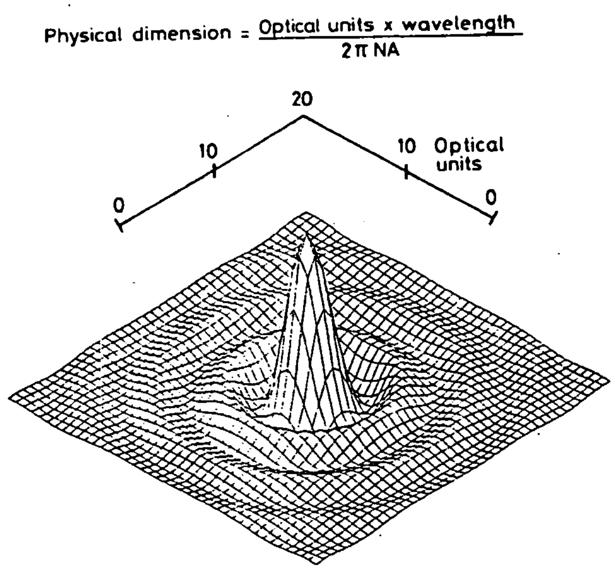

Fig 3 Airy disc (amplitude)

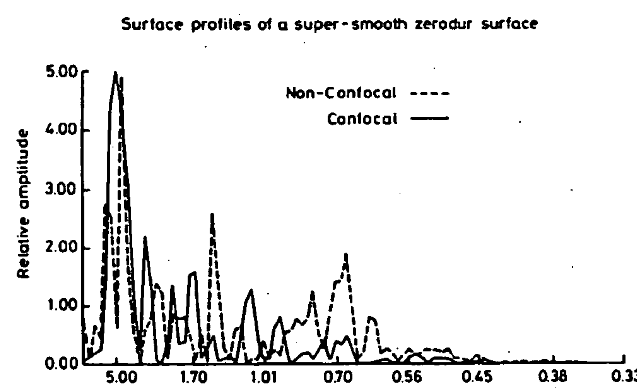

Fig 4 Surface wavelength μm

The measurements were obtained by firstly scanning in a confocal mode and then removing the apodising aperture in order to scan across the identical area on the surface of the specimen. When the NPL instrument is fitted with a 0.5 NA objective and 20 μm diameter pinhole in front of the photodetector, the confocal aperture represents a projected surface area of less than 1 μm, removing the probe amplitude variations greater than the central disc. Inspection of the two Fourier transform traces indicated a greater response to shorter surface wavelengths in the conventional mode of operation than in the confocal one. The many differences between these traces highlight the complexity of the system/sample interaction in an interferometer of this type with a probe beam approaching the diffraction limit.

4. CONCLUSION

The results of surface profile measurements of silica and Zerodur specimens have been discussed and confirm that optical interferometry provides an extremely sensitive tool for examining the profiles of polished surfaces. They have also indicated the care that must be taken in the interpretation of the measurements achieved using this technique, as they are directly dependent upon both the energy distribution within the interfering beams and the characteristics of the surface roughness.

It is worth noting that not only does the 'common-path' design of these instruments make them insensitive to environmental conditions enabling high measurement sensitivities to be obtained but in addition it makes them simple to apply in practice.

5. ACKNOWLEDGEMENTS

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